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Evaluation of Particulate Emission Factors for Vehicle Tire Wear

PEDCo-Environmental, Inc, Kansas City, MO

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Vehicle-related emissions are a major contributor to urban particulate concentrations. One of the vehicle-related emission sources is tire wear. It is estimated that 3.2×10^2 to 7.2×10^8 kg of tire wear debris are generated each year in the United States. Particles from tire wear have been identified by microscopic analysis as a significant component of samples taken from roadside high volume particulate samplers.

The currently available emission estimate for tire wear, presented in Compilation of Air Pollutant Emission Factors (AP-42), is 0.20 g/veh-mi for a four-wheeled light duty vehicle. This emission factor is widely used in regional particulate analyses to estimate emissions from tire wear; however, this factor needs to be reviewed, based on studies and test data released since its publication.

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SECTION 1

INTRODUCTION

Vehicle-related emissions are a major contributor to urban particulate concentrations. One of the vehicle-related emission sources is tire wear. It is estimated that 3.2×10^8 to 7.2×10^8 kg of tire wear debris are generated each year in the United States.[1,2,3,4] Particles from tire wear have been identified by microscopic analysis as a significant component of samples taken from roadside, high volume, particulate samplers.[5,6]

The currently available emission estimate for tire wear, presented in Compilation of Air Pollutant Emission Factors (AP-42), is 0.20 g/veh-mi for a four-wheeled, light-duty vehicle. This emission factor is widely used in regional particulate analyses to estimate emissions from tire wear; however, this factor needs to be reviewed, based on studies and test data released since its publication.

Particulate from tire wear is generated as a result of forces existing between the tire and the road surface. These forces are transmitted by the tire to the road surface during acceleration, deceleration, and directional changes. Owing to tire elasticity, tire deformity occurs with differences in the magnitude or direction of travel that occur as the operator controls the vehicle.

The deformity of a tire negotiating a curve results in a kidney-shaped contact area (shown in Figure 1). The front part of the tire adheres to the road by friction. Elastic forces arising from distortions in the rear part of the tire overcome friction, causing the tire to react horizontally and to slide over the road. Adhesion in the front part of the tire is instrumental in achieving a change in direction, while abrasion is confined to the rear part of the contact area. Similar action occurs during braking and accelerating, but the direction of the strain and sliding is then circumferential.

Several factors influencing the magnitude of abrasion in the rear part of the contact area have been studied. These factors are both external (tire forces, pavement characteristics, and environmental conditions) and internal (tread composition, tread design, and other tire features). Tire forces have been shown to

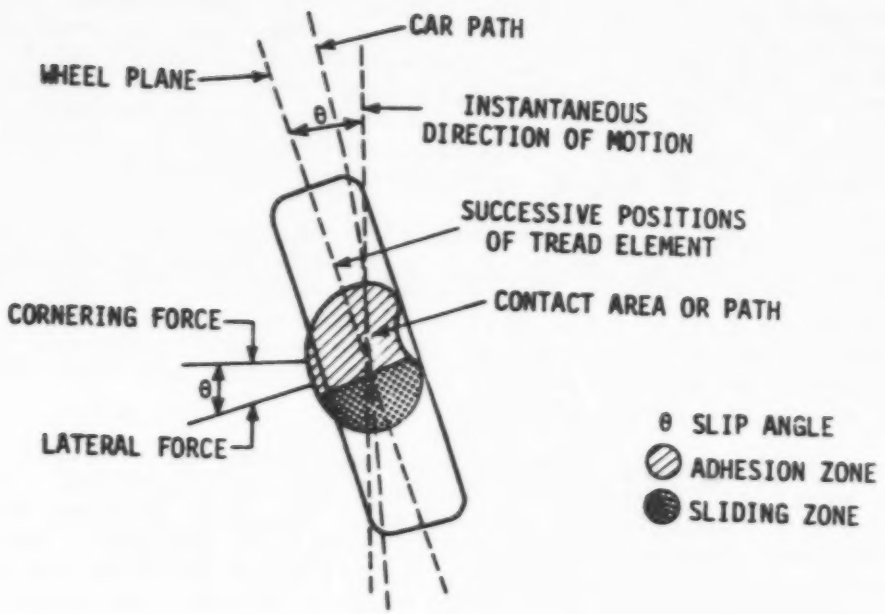

Figure 1. Simplified schematic of tire that is generating cornering force.

Source: Reference 7

be the major source of tire wear.[7,8] These forces include longitudinal forces of driving and braking and, most significantly, lateral or cornering forces. Pavement type has also been shown to influence the amount of tire wear.[9] Studies have also measured tire wear as a function of tire tread temperature.[8,10] Many studies have been performed to estimate wear as a function of tread composition, tread design, or tire type. Most of these studies were done to evaluate performance ratings, relative to a control tread stock, rather than to evaluate the rate of wear per mile of travel. Several experiments have defined what is known as wear test severity. From an analytical and experimental standpoint, there are three wear severity classifications: tire force severity (intensity and distribution of tire forces), abrasive surface severity (type and condition of pavement), and weather temperature severity (tire and ambient temperature).[7]

SECTION 2

METHODS OF EVALUATING TIRE TREAD WEAR

Testing of tires in the past has been done for two reasons: control tests on samples selected at random from current production; development tests designed to evaluate the effects of experimental features of design, of compounding, or of changes in processing procedures.[10] More recently, the concern over particulate and gaseous emissions resulting from tread wear has prompted experiments dealing with tread loss and airborne tire debris.

Direct measurements of tire wear are made by two general methods, indoor and outdoor testing. Laboratory abrasion tests can only be justified if they correlate with actual service performance. These indoor tests are usually run on a machine that consists of a steel roller against which single or multiple tires are pressed at controlled loads. Outdoor tests are performed using specially built trailers, single test vehicles, or a fleet of test vehicles selected at random or contracted for. Tread wear rates are determined either by weight loss or tread-depth loss of the test tire. In addition, indirect estimates of tread wear are obtained through ambient air sampling in a tunnel or near a roadway.

The methods used in these tire wear studies are listed in Table 1, with advantages and disadvantages of each method outlined therein. References for data derived by each method are also included.

Of the seven test methods identified in Table 1, indoor testing on a chassis dynamometer and outdoor vehicle testing (either single vehicle or a fleet) are the methods determined to be most representative of actual tire wear. The indoor testing provides a method for the determination of particle size distributions, while the outdoor testing provides a measure of the wear rate of a tire in actual use.

Because both test methods directly measure tire miles traveled and tire tread wear, the test results are easily compared with one another. Factors such as tire inflation pressure, road surface type, tire tread temperature, and tire force can be closely controlled to provide reliable results in both cases. The absolute wear rate may not be equal for both tests, but the

TABLE 1. METHODS OF EVALUATING TIRE TREAD WEAR

Technique	Advantages	Disadvantages	References
Indoor testing, on chassis dynamometer or tire abrasion mat	Low test cost Relatively rapid procedure Possible ±10% precision Can test easily under varied conditions of load, speed, tire inflation, etc. No interference from adverse weather conditions Tire surface temperature can be measured with relative ease Particle collection method is simple Particle size determination is possible	No wear from directional control Tire in contact with the same surface during entire test, producing elevated tire surface temperature Roller surface is not precisely comparable to a road surface Different forces associated with rubber tire in contact with a roller or mat than on pavement Tire acquires a "sticky" appearance not typical of on-road operation Steel roller does not have same effect as a road surface on carcass performance Fugitive dust may interfere with results	2,4,9,10,[a] 11,12,13[a]
Outdoor testing specially built trailer	Accelerated procedure provides short testing periods Precise control of test conditions possible Typical of normal tire use Cornering force can be varied Forces compare well with actual forces encountered Tire comparisons can be made under exactly equal tire forces Independent study of three major external tire forces is possible Accurate record of operating variable is obtained	Testing costs can be high Accelerated condition may cause abnormal tire wear Restricted conditions of road surface and climatic conditions Tire static load and velocity have only minor contributions; both are major forces encountered in actual use Debris is not collected for particle size determination	7,10,[a]13[a]

[a] No original data presented.

(continued)

TABLE 1 (continued).

Technique	Advantages	Disadvantages	References
Outdoor testing, single wheel	Catch plate mounted behind tire provides convenient sampling Normal driving conditions provide wear abrasion Particle size determination is possible Accurate record of operation is obtained	Catch plate sometimes lost during test Small particles are swept away by airflow and neglected from analysis Fraction of particles caught cannot be quantified Collection efficiency can be as low as 4.5% Material balance cannot be established Lower limit of detection is 5 μ Below 5 μ, dirt and rubber particles look similar	3
Outdoor testing, single vehicle or fleet of vehicles	Tread wear measured by weight or tread depth loss Closely controlled test conditions sometimes possible Random sampling possible Wear measured under normal use Accelerated tests can be conducted Sectional tires can be used to determine an average wear rate Results can be compared with indoor testing results Accurate and detailed operation records may be available	Long periods of testing required Measurements difficult to obtain for a random fleet sample Road surface and climatic effects difficult to evaluate Maintenance conditions may not be under control of experimenter Tire sizes and types are limited Service records may be incomplete Assumptions required on the density of the average tire Measurements may be affected by gaseous breakdown of tire No particle size determination possible	2,7,9,10,[a] 13,[a]14,15

[a] No original data presented.

(continued)

TABLE 1 (continued).

Technique	Advantages	Disadvantages	References
Rubber abrasion equipment (e.g., PICO abrader)	Low cost Rapid test Particles easily collected Weight measurements provide precise analysis	Testing done under completely different conditions than normal tire use Rubber curing is an important factor to be considered Mechanics of wear are not the same as actual tire wear	16[a]
Tunnel air sampling	Difference in selected compound (e.g., SBR) can be attributed to tire wear Can measure submilligram amounts of SBR Relatively simple sampling procedure	Analytical method has possible interference from diesel fuel particulate Removal of interfering substances also removes SBR Large air sample required to extract detectable amounts of SBR, composing only 0.1% of the sample Deviation in the range of ±20% can be expected Only 2 to 7% of SBR is airborne Only 65 to 70% of SBR can be collected Not all treads contain SBR	6,17,[a]18,[a]
Roadside high volume sampling	Particle size distribution may be possible	Only rough estimates of tread wear can be made All of the disadvantages for tunnel air sampling also apply	5

[a] No original data presented.

fractions occurring as airborne or sedimentary in the outdoor tests can be assumed based on the fractions occurring in the indoor tests.

Outdoor trailer testing is not considered in the emission factor determinations. The advantages listed show that precise control of conditions is possible and forces compare well with those encountered in actual use, but the disadvantage of accelerated wear is considered more important. Abnormal tire wear under these accelerated conditions can easily result in erroneous, although seemingly correct, estimates. Outdoor single wheel testing is also eliminated from wear rate considerations. The major reason for this is that the collection method is inadequate for quantifying particulate emissions from tire wear. This is also the main reason for eliminating the tunnel air sampling and roadside high volume sampling methods. The Pico method abrades only a sample of rubber in a completely different manner than actual tire abrasion. This method is used primarily to compare different rubber compounds and does not appear acceptable for determination of tire wear.

As indicated in Table 1, there are five studies using indoor test facilities that produced original data.[2,4,9,11,12] The indoor facilities included a chassis dynamometer, particulate collection devices, and various control and monitoring devices. In one experiment, gas samples were also collected. The chassis dynamometer is an instrument that allows an actual car or tire to be driven on rollers, while control is maintained over speed, load, and sometimes slip angle. In four of the tests, the contact rollers were constructed of steel; in one, the roller was a 36-mesh abrasive wheel with 120-mesh carborundum grit. The latter roller was constructed to simulate an actual road surface. Most of the experiments had no control over slip angle, so no wear from directional control was produced.

The particulate collection system usually consisted of a box completely enclosing the tire being tested. Airborne particles were measured in a known volume of air drawn through the box to the measurement device. In some cases, particle size determinations were made using an Anderson sampler or a similar device. Sedimentary particles settled to the bottom of the box and were collected separately for weighing. Speed, load, and miles traveled were monitored in all tests. Measurements of tread depth and tire weight were sometimes made, in addition to particle collection, in order to arrive at appropriate weight loss conversion factors when comparing laboratory and outdoor road tests.

The main advantages of indoor testing are that test conditions are easily controllable, particle collection is simple, and particle size determinations are possible. The main disadvantage associated with this type of testing is that the tire is in

contact with the same surface during the entire test, which can lead to elevated tire temperatures. Also, wear from directional control is sometimes neglected, different tire forces exist on the roller than on a pavement, and the steel roller produces a "sticky" tire appearance quite unlike the appearance of a tire driven on pavement.

Two of the indoor testers also performed outdoor vehicle tests for direct comparison.[2,9] Three other sources of original outdoor vehicle test data are also available.[7,14,15] Two of the five testers used single vehicles and three used fleets for determination of average wear rates. Some of the outdoor tests also employed trailer testing systems but, as stated earlier, these data are not considered.

The source of the best test data is believed to be average fleet values. In three tests, the vehicles were tested under controlled conditions of tread composition, inflation pressure, speed, loading, road surface, and tire rotation order. One study used owner-operated vehicles. These volunteers maintained the tires in whatever fashion was typical for them, and thereby provided actual user data. Most of the tire wear values are expressed as a wear index, or the ratio of the test tire to a control tire times 100. It was, therefore, necessary to have knowledge of the wear rate of the control tire. The tire wear rates were obtained by tire tread depth measurements or tire weight measurements. Tests that measure wear rate by both methods provide conversion factors for emission factor calculations. Several tests were conducted to determine tire wear as a function of a particular factor such as temperature or road surface.

As apparent in Table 1, the main advantages of outdoor vehicle testing are that wear measurements are made under actual road conditions and that random sampling is possible. In the case of fleet tests, conditions can be closely controlled and accurate operating data are available. The main disadvantages associated with outdoor vehicle tests are the long testing periods required, the difficulty in controlling maintenance conditions for random fleets, and the lack of particle size distribution data. In addition, if weight measurements are made, conditions of tire inflation and humidity must be equalized before valid measurements can be obtained.

All of these limitations must be considered before, during, and after tire wear testing. There are two means of minimizing the test disadvantages. The first necessitates close control of the following conditions: tire inflation pressure and humidity, vehicle speed, tire loading, surface texture, tire rotation order, vehicle maintenance, length of testing, and tire forces.

The second demands an awareness of important testing requirements: wear rate measurements, particulate collection devices, and tire tread composition.

SECTION 3

CALCULATION OF TIRE WEAR ESTIMATES

Several units are commonly used to measure tire wear and particulate emissions from tire wear. The following units have been used in one or more of the tests to determine tread depth and weight loss:

- mil/mi; mil/1000 mi (1 mil = 0.001 inch)
- mg/km
- g/veh-mi; mg/mi; mg/1000 mi
- cm^3/1000 mi
- cm^3/1000 km
- wear index $\left(\frac{\text{wear of control tire}}{\text{wear of test tire}}\right)(100)$

The current particulate emission factor from AP-42 is in g/veh-mi for a four-wheeled, light-duty vehicle. This factor can be easily used with activity data (vehicle miles traveled) to compute an emission inventory. Therefore, it is desirable to express all test data in these units. Example conversion calculations are shown here to demonstrate the process and the assumptions necessary for conversion.

1. mil/mi to g/veh-mi -

   $(\text{mil/mi})(5\ \text{g/mil})^a = 5\ \text{g/veh-mi per mil/mi}$

   or

1a. $(\text{mil/mi})(.001\ \text{in./mil})(29.3\ \text{in.})^b(\pi)(4.33\ \text{in.})^c(59\ \text{lb/ft}^3)^d (\text{ft}^3/1728\ \text{in.}^3)(454\ \text{g/lb}) = 6.28\ \text{g/veh-mi per mil/mi}$

2. mg/km to g/veh-mi -

   $(\text{mg/km})(1.609\ \text{km/mi})(\text{g/1000 mg}) = 1.609 \times 10^{-3}\ \text{g/veh-mi per mg/km}$

---

a Reference 7
b Reference 2, average measured tire diameter
c Reference 2, average measured tread width
d Reference 19, assumed density of rubber

3. $cm^3/1000$ mi to g/veh-mi -

$$(cm^3/1000\ mi)(59\ lb/ft^3)^d\ \frac{(454\ g/lb)(ft^3/28{,}360\ cm^3)}{1000} = 0.946 \times 10^{-3}\ g/veh\text{-}mi\ per\ cm^3/1000\ mi$$

4. $cm^3/1000$ km to g/veh-mi -

$$(cm^3/1000\ km)(0.946 \times 10^3\ g/veh\text{-}mi\ per\ cm^3/1000\ mi)(1.609\ km/mi) = 1.52 \times 10^{-3}\ g/veh\text{-}mi\ per\ cm^3/1000\ km$$

5. wear index to g/veh-mi -

some measure of tire wear for a control tire is required

$$\text{wear of test tire} = \left(\frac{\text{wear of control tire}}{\text{wear index}}\right)(100)(\text{appropriate conversion factor})$$

These conversion factors were applied to data from eight tire wear tests that used either an indoor test facility or outdoor vehicle testing to arrive at the emission factors presented in Table 2.

Examination of Table 2 reveals a range of emission factors from 0.12 to 0.51 g/veh-mi. These values represent total emissions (including gaseous emissions) and therefore refer to weight lost in grams per vehicle mile traveled (VMT). The first factor reported from Reference 2, 0.409 g/veh-mi, was derived from measurements taken from 17 owner-operated vehicles that accumulated a total of 84,590 vehicle miles. Tread depth measurements were made on each tire in 18 different locations around the tire, and odometer readings were recorded. An average annual tire tread loss was calculated by weighting winter and summer wear rates by their respective mileage accruals, and by converting to g/veh-mi using emission calculation method 1a. Four control vehicles were also operated. Mileage accruals on two of these vehicles were 2960 and 5988 VMT and calculated wear rates were 0.260 and 0.340 g/veh-mi. The second factor extracted from Reference 2, 0.183 g/veh-mi, was determined through indoor testing methods. Two vehicles were operated on a dynamometer for a total of 100 miles. The mode of operation was chosen to simulate a normal driving cycle. Particle size distribution measurements were conducted and results indicated that 50 percent of the emissions are in the respirable particulate size range. This distribution was then applied to the fleet value to obtain an estimate of the respirable particulate emitted by the fleet vehicles. Reference 2 and Table 1 indicate, however, that several disadvantages are associated with this testing facility.

TABLE 2. EMISSION RATE ESTIMATES FROM TIRE TREAD WEAR[a]

(g/veh-mi)

Total emissions	Emission range	Airborne particulate, <30μ	Respirable particulate, <3.5μ	Test type	Ref. No.
0.409	0.360-0.794	b	0.204[c]	Outdoor fleet	2
0.183	0.178-0.185	b	50%	Indoor composite	2
b	b	0.008	b	Typical indoor	4
0.34	0.27-0.40	b	b	Outdoor fleet, control car	7
0.51	0.22-0.87	b	b	Outdoor fleet, cornering force tests	7
0.44	0.40-0.50	b	b	Outdoor, as a function of tire temperature	7
0.248	0.161-0.342	b	b	Outdoor fleet, in two states	9
0.14	0.075-0.200	0.003-0.008	b	Indoor, combination	11
0.12	0.09-0.18	b	b	Outdoor fleet, as a function of tire temperature	14

[a] Emission rates are for a four wheeled light duty vehicle.
[b] No data.
[c] Estimated value based on indoor chassis dynamometer tests.

The most representative emission estimates of total tire wear are those presented in Reference 7. This study was undertaken to determine the effect of the more important elements of tire wear, these being tire force, pavement texture, and tire surface temperature. Tire force and pavement texture measurements were made under accelerated conditions and most values reported are the results of trailer testing. Control vehicles were also operated for the tire force studies; tire force was shown to be the major factor of the three elements studied. All wear rates were determined by measurements of the tread depth loss and by conversion to g/veh-mi using emission calculation method 1. The first value obtained from Reference 7, 0.34 g/veh-mi, is determined to be the average wear rate of the control fleet. The wear rates obtained from the control fleet were also compared with the trailer wear rates. Correlation coefficients showed good correlation between fleet tests and low-severity trailer tests ($r = 0.95$ at 150 lb cornering force), and equally good correlation at high-severity trailer tests ($r = 0.97$ at 400 lb cornering force). The average value of these cornering force tests is 0.51 g/veh-mi, with a range of 0.22 to 0.87, as shown in Table 2. This value, however, was obtained in accelerated tests that may have produced abnormal wear. The last factor extracted from Reference 7, 0.44 g/veh-mi, was determined as a function of tire temperature studies on fleet vehicles. The wear rates showed good linearity, when plotted against tire surface temperature, suggesting an accurate determination of tire surface temperature and tread loss. The wear rate determined as a function of pavement texture is not shown in Table 2. This study was done with trailer tests under accelerated conditions, and also considered slip angle as one of the study elements. Because slip angle on trailers is produced in a manner different than slip angle produced under actual vehicle operation, the values obtained have been omitted from the emission factor determinations. The average value obtained from these tests, however, agreed well with the others reported and was determined to be 0.36 g/veh-mi.

Over 100,000 vehicle miles of testing were performed to arrive at the emission factors presented in Reference 9. The average of all values is 0.248 g/veh-mi. Fleet testing was performed in Texas and California by two testing companies and in the laboratory. These tests were undertaken to determine the relationship between specific abrasion of different tire tread stocks and the equivalency of road and laboratory testing methods. Laboratory abrasion was performed using a 36-mesh abrasive wheel, with 120-mesh carborundum grit flow rate adjusted to the rate of abrasion. Tire wear measurements were made by the tread depth loss and tire weight loss methods. Values were reported as cm^3/1000 mi; conversion to g/veh-mi was performed using emission calculation method 3. Reference 9 presents six different wear rates representing tests of three different tread stocks in the two states. In some tests, the same tires were used in both

states. The average of all reported values is 0.248 g/veh-mi, with a range of 0.161 to 0.342 as shown in Table 2. It was found that the laboratory abrader conditions exaggerated losses at lower severities for some tread stocks, but showed reasonably good agreement with road abrasion indexes for others. The discrepancy at lower severities is believed to result from rubber oxidation effects. Some differences were also observed between the results obtained from the two states, and these differences were believed to be valid because of the surface texture of different pavements on the two test routes.

The value reported in Reference 11, 0.14 g/veh-mi, was obtained at an indoor test facility using a steel roller apparatus similar to the dynamometer discussed in Reference 2. Five testing modes were used; the value reported is the result of a combination of all of these test modes. The testing was performed over 150 tire miles; all wear products were collected and analyzed for sedimentary and airborne particulate, as well as gaseous products. Material collection efficiency was checked periodically by weighing the tire before and after each test but, once a material balance was made, no further weight loss measurements were performed. Measurement of airborne particulate revealed that only 1 to 10 percent of the total wear products occurred as airborne particulate; the majority were sedimentary. Furthermore, it was observed that this percentage is dependent on tire wear rate, with higher percentages of airborne particulate produced at lower wear severities. These observations conflict with those reported in Reference 2, where it was concluded that 50 percent of all emissions from tire wear are in the respirable particulate size range. The upper value of airborne particulate emissions in Reference 2 is comparable to that in Reference 4, which reported a typical value of 0.008 g/veh-mi using an indoor testing facility.

The tests reported in Reference 14 were performed to determine the effect of tire surface temperature on the amount of tread wear. Trailers and a fleet of vehicles were used for these experiments. All wear measurements were made by weighing the tires every 200 miles, which also provided for a regular tire rotation scheme. The values are reported as wear index (as a function of temperature), with the tire wear of the control vehicle expressed in $cm^3/1000$ km. Emission calculation methods 4 and 5 were used for conversion to g/veh-mi. In order to calculate an emission factor from the data presented, it was necessary to use distribution plots of tire surface temperatures. Wear indexes were determined for 12 different temperature ranges, each 5°C, either long distance or commuter travel. These indexes were multiplied by the percent of vehicle operation time when the tire surface temperature was in the specified temperature range. This yielded a wear rate for long distance and commuter travel. A weighted average of these two values yielded the emission factor,

0.12 g/veh-mi, which appears in Table 2. The calculation process was cumbersome and reflects temperature variation readings taken from one test vehicle over a period of 13 months. Other investigators have commented on the difficulty of measuring tire surface temperature and, for that reason, it appears that these calculations are subject to a large degree of error.

The eight emission factors presented in Table 2, each the result of separate testing, were ranked according to test approach and sample size. These values are listed in Table 3 with a brief rationale for the ranking decision; they are listed in a descending order of apparent accuracy.

The average of the eight emission factors is 0.30 g/veh-mi. As mentioned several times previously, however, indoor tests produce wear on the test tire that is quite different from wear produced in normal operation. Removing the indoor values yields an average emission factor of 0.34 g/veh-mi. This value represents a more accurate estimate of emissions from tire wear, although the factors ranked 5 and 6 also have inaccuracies associated either with the testing or with the calculations used. Therefore, these two factors are also omitted from calculation of the average value. This yields an average of 0.36 g/veh-mi. Thus, the most representative emission factor for tire wear is in the range of 0.30 to 0.36 g/veh-mi, depending upon which test results are included in the determination.

It is more desirable to choose an emission factor from the literature that best represents the investigation efforts and conclusions reached by all research studies, rather than to adopt a value that represents an average of all work. This provides a value determined to be most representative for future use. Reviewing the list of emission factors presented in Table 3, it is apparent that there is one value within the range determined to best represent all work done in this area. That value is 0.34 g/veh-mi. This is also the value that is ranked highest in accuracy, as determined by testing methods, reproducibility, and data base.

MECHANICS OF TIRE WEAR DEPOSITION

The preceding discussion suggests the value of 0.34 g/veh-mi for use in estimating tire wear emissions. Because this emission factor is based on tread depth loss during outdoor vehicle testing, it represents total tread loss (converted to weight loss) per mile of operation. It then is necessary to discover where this material is lost. Many studies have been undertaken to make this assessment.

Figure 2 presents a schematic of possible methods of weight loss and particulate emission during the tire wear process. As

TABLE 3. RANK OF EMISSION FACTORS

Rank	Factor, g/veh-mi	Reason	Reference
1	0.34	This value is the average wear rate of a fleet. All other tests performed in this study support this value.	7
2	0.44	From the same reference as the above value, this factor is the average value of wear as a function of temperature tests. Temperature appears to be a major factor in the wear process.	7
3	0.248	This value is the average of fleet tests performed in two states. Over 100,000 miles of testing were driven.	9
4	0.409	This value is the average wear rate of a randomly selected fleet operated by vehicle owners in actual service over a period of 12 months.	2
5	0.12	Derived from wear as a function of temperature studies, this value requires assumptions as to the annual distribution of tire tread temperatures, thereby allowing for analysis errors.	14
6	0.51	The result of cornering force tests, this value was arrived at in accelerated tests possibly with unusual forces associated with testing.	7
7	0.183	These values were determined in indoor testing facilities and should be considered less accurate than outdoor testing results.	2
8	0.14		11

presented in this figure, there are four fractions of emissions from tire wear that can account for the measured weight loss. These fractions are E_t (tire wear directly transferred to the road surface), E_s (sedimentary tire wear particulate), E_a (airborne tire wear particulate), and E_g (gaseous tire wear product). Very little work has been done to determine the amount of tire wear products which are gaseous in nature, but Myslinski concluded that less than 0.064 percent of the wear products are volatilized.[12] It can be concluded that the gaseous fraction is an insignificant portion of the 0.34 g/veh-mi factor.

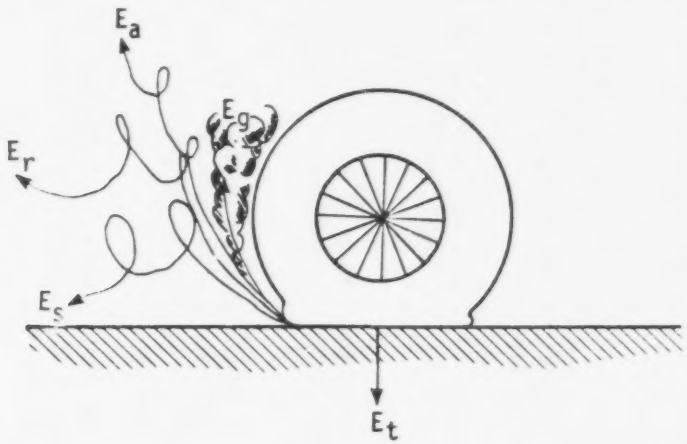

Figure 2. Mechanics of material loss and emissions from tire wear.

The most significant portion of tire wear emissions occurs as sedimentary particles and as particles transferred directly to the road surface. It is estimated that these fractions account for up to 90 percent of the material lost during the tire wear process.[2,3,4,6,11,18] Just as tire skid marks seem to disappear with time, so these fractions of tire particulates are removed from the road surface. This removal process occurs in one of several ways. Some of these particles are removed by the washing effect of rainfall or by the action of a street sweeper. Displacement of this material occurs when passing vehicles pick it up, either by the action of the tires or by the vortex produced as they pass. This material is then displaced to the roadside and is usually found in measurable concentrations, decreasing with distance from the roadway up to 5 meters away. Further removal occurs as a result of oxidation processes on the rubber, which degrades the material into gaseous products.[4,11] Another action of passing vehicles is the grinding of large particles into smaller particles. Some of these particles are then able to become airborne, and make up the fraction labeled E_r in Figure 2. E_r is the portion of reentrained particulate from paved streets that is attributable to tire particulates.

An analysis of the deposition processes leading to the accumulation of particulate matter on paved streets suggests that 10 lb of tire rubber are deposited on a typical curb-mile of road each day.[20] This amount constitutes 4.2 percent of the total particulate loading on a typical street, and is defined in Figure 2 as E_t and E_s. This study also determined that approximately 50 percent of this deposited material later becomes reentrained (E_r). This material then becomes airborne and can be transported long distances before settling again.

The final fraction that accounts for tire weight loss is E_a, the fraction of particulate from tire wear that is initially airborne. This fraction is usually estimated from indoor test results to be 10 percent of the total weight loss.[2,4,11,21] This fraction of the tire wear emissions, together with E_r (the reentrained portion), is what eventually reaches high volume samplers.

Some indirect quantification of $E_a + E_r$ is possible in studies using high volume samplers to determine the impact of tire rubber on air quality readings. One of these studies collected tire rubber particulate on glass fiber filters. The tire rubber accounted for 2.5 percent of the total reading near a roadway.[18] These results were duplicated in another study of particulate calculated near roadways, where 2.5 percent of the particulate was of vehicle tire origin.[5] These two studies confirm the conclusions reached in Reference 20: 4.2 percent of the total particulate loading on streets is tire rubber, and 50 percent of this material is eventually reentrained and becomes airborne. This can be seen in the following calculations:

Tire rubber	=	4.2% of total street loading
Reentrained material	=	50% of deposited material
Reentrained tire rubber	=	(0.50)(4.2) = 2.1% of total reentrained material

This 2.1 represents the percent of reentrained particulate collected at high volume samplers near roadways that is of tire rubber origin.

The initially airborne fraction of particulate is also collected on samplers. In order to calculate the total fraction of particulate contributed by tire wear, the following equation can be applied:

$$\text{Tire wear fraction} = 2.1 + \left(\frac{(2.1)(E_a)}{(E_{total} - E_a)(0.50)} \right)$$

where 2.1 = percent of total reentrained material contributed by tire wear

E_{total} = total tire weight loss (100%)

E_a = percent of E_{total} that is initially airborne (10%)

0.50 = fraction of deposited material that becomes reentrained

Substituting these values yields a total of 2.6 percent of the high volume sample contributed by tire wear particulate. This agrees closely with References 5 and 18.

SECTION 4

SUMMARY AND CONCLUSIONS

It has been stated that tire wear is the result of frictional forces imparted by the tire to the road in order to maintain control of a moving vehicle. The wear process is a function of external and internal tire forces, as well as speed, load, and environmental conditions. Cornering forces, pavement type, and temperature have all been studied as independent variables affecting the rate of tire wear and these studies have produced comparable emission factors.

The identification of particulate emissions from tire wear is very complicated. As discussed in this report, several methods are currently used to evaluate the weight lost from tires during operation. It has been determined that the most accurate emission factor is 0.34 g/veh-mi, representing total weight loss. The airborne fraction of this factor is 10 percent, or 0.034 g/veh-mi, indicating that 0.306 g/veh-mi are either directly transferred to the roadway or emitted as sedimentary particulate. If it is then assumed that 50 percent of this amount is reentrained, a total of 0.153 g/veh-mi is added to that fraction which is initially airborne. Summing the airborne and reentrained fractions yields an overall emission factor for airborne particulate from tire wear of 0.19 g/veh-mi. The following is a summary of particulate emissions from a four-wheeled, light-duty vehicle.

Fraction	Percent of total	Emission factor, g/veh-mi
Total weight loss	100	0.34
Initially airborne particulate	10	0.03
Sedimentary and direct transfer to road surface particulate	90	0.31
Reentrained particulate	0.5(90) = 45	0.16
Total airborne particulate	10 + 45 = 55	0.19

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